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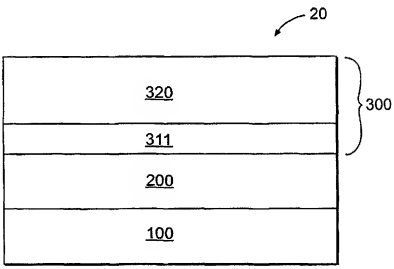
(54) Title: ORGANIC LIGHT EMITTING DIODE DEVICE WITH HIGH WORK FUNCTION METAL-OXIDE ANODE LAYER AND METHOD OF FABRICATION OF SAME



(57) Abstract: An organic light emitting diode (OLED) device (20) is disclosed, having a bottom electrode (100), an organic stack (200) for emitting light disposed on bottom electrode (100), and a top electrode (300) disposed on organic stack (200). Top electrode (300) further comprises a lower portion or thin metal film layer (311) disposed on organic stack (200) and a relatively thick, transparent upper portion (320) of indium tin oxide (ITO). The process of sputtering the ITO layer oxidizes thin metal film layer (311) to provide desirable injection properties, wherein, for example, the injector layer thickness is in the range of from about 10 Å up to about 100 nm.

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ORGANIC LIGHT EMITTING DIODE DEVICE WITH HIGH WORK FUNCTION METAL-OXIDE ANODE LAYER AND METHOD OF FABRICATION OF SAME

Cross-Reference to Related Applications

This application relates to and claims priority on United States Provisional Application Serial No. 60/149,719, filed August 20, 1999 and entitled "Organic Light Emitting Diode Device Having High Work Function Metal-Oxide Anode Layer and Method of Making."

Field of the Invention

The present invention relates to organic light emitting diode (OLED) devices that are made using a sputtering process to form a top electrode in the OLED. In particular, the present invention relates to the formation of a top electrode in which a metal layer (for example, molybdenum) is oxidized to form a portion of the top electrode with desirable injection properties.

Background of the Invention

Organic light emitting diodes (OLEDs) have been known for approximately two decades and are useful for the production of visual displays. All OLEDs work on the same general principles. One or more layers of semiconducting organic material are sandwiched between two electrodes. An electric current is applied to the device, causing negatively charged electrons to move into the organic material(s) from the cathode. Positive charges, typically referred to as holes, move in from the anode. The positive and negative charges meet in the center layers (i.e., the organic material), recombine, and produce photons. The wavelength of the photons -- and consequently the color of the emitted light -- depends on the electronic properties of the organic material in which the photons are generated.

In a typical OLED, at least one of the electrodes is transparent. The cathode may be constructed of a low work function material. The holes may be injected from a high work function anode material into the organic material. Typically, the devices operate with a DC

bias of from 2 to 30 volts. The films may be formed by evaporation, spin casting, self-assembly or other appropriate film-forming techniques. Thicknesses typically range from a few mono layers to about 2,000 Angstroms.

In a typical matrix-addressed OLED display, numerous OLEDs are formed on a single substrate and arranged in groups in a regular grid pattern. Several OLED groups forming a column of the grid may share a common cathode, or cathode line. Several OLED groups forming a row of the grid may share a common anode, or anode line. The individual OLEDs in a given group emit light when their cathode line and anode line are activated at the same time.

OLEDs have a number of beneficial characteristics. These include a low activation voltage (about 5 volts), fast response when formed with a thin light-emitting layer, and high brightness in proportion to the injected electric current. OLEDs are currently the subject of aggressive investigative efforts.

An OLED may be designed to be viewed either from the "top" -- the face opposite the foundational substrate -- or from the "bottom", i.e., through the substrate, from the face opposite the light emitting layer. Whether the OLED is designed to emit light through the top or the bottom, the respective structure between the viewer and the light emitting material needs to be sufficiently transparent, or at least semi-transparent, to the emitted light. In many applications it is advantageous to employ an OLED display having topside light output. This permits the display to be built on top of a silicon driver chip for active matrix addressing.

Currently, the most favored type of top-emitting OLEDs are those in which the top electrode, or top conductive layer, is a cathode. A top-emitting OLED device from the prior art is shown as Fig. **1**. Known OLED device **10** may include a bottom conductive layer or electrode **100**, which typically is patterned silicon. A stack of one or more organic layers **200** is formed on bottom layer **100**. It is this organic layer that generates light. Top conductive layer or electrode **300** is formed on organic layers **200**. Top conductive layer **300** may comprise lower layer **310** and upper layer **320**. Lower layer **310** may be a thin evaporated magnesium silver (MgAg) alloy film if a cathode, or a thin evaporated gold (Au) or platinum (Pt) alloy film if an anode. These metal/alloy films provide desirable injection

properties. Upper layer **320** may be indium tin oxide (ITO) which provides desirable sheet conductivity and transparency properties. Top conductive layers **310** and **320** may comprise either a cathode or an anode, but in the presently favored known structures, these layers provide the device cathode.

In order for the light generated by organic layers **200** to pass through top conductive layers **310** and **320**, these top layers should be largely transparent to the wavelength of light generated. The "transparent" requirement of the top conductive layers in a top-emitting OLED is typically fulfilled by selecting a very thin lower layer **310** of a MgAg alloy, and by selecting ITO as the material for upper layer **320**. Lower layer **310** is typically only 50-200 Å thick, which does not block much visible light. ITO has a desirable blend of transparent and conductive properties in the thickness that is required for a top-emitting OLED.

Typically, the top conductive layer of ITO is formed using a sputtering process. More specifically, a DC or AC magnetron process may be used to direct an argon plasma to an ITO target in order to sputter the ITO onto the OLED. To achieve an ITO layer with a desirable blend of transparency and conductivity properties, additional oxygen may be provided in the argon plasma. The oxygen which is necessary for the sputtering process may have a negative impact on both the underlying MgAg alloy layer **310** and the underlying organic layers **200**. The oxygen in the argon plasma damages (*i.e.* oxidizes) the underlying layers, and is particularly harmful in this respect to the Mg in the thin evaporated MgAg alloy film in the top-emitting cathode structure of known OLEDs. In the structure of Fig. 1, if oxygen from the ITO plasma oxidizes the MgAg film, the resulting magnesium oxide (MgO) may over-insulate the organic stack from the ITO. Further, if the MgAg layer is more than a few nm thick, this may also over-insulate the organic stack. Thus, the desirable practice of increasing the level of oxygen in the argon plasma, to achieve low ITO sheet resistance, carries with it the undesirable side effect of increasing the risk that the MgAg film and organic layers in the OLED will be damaged (*i.e.*, oxidized) by oxygen.

Presently, the negative impact of oxygen in the argon plasma on the injection layer of the top conductive layer (MgAg) and the organic layers in the OLED remains largely unaddressed. Thus, there is a need for an OLED structure and process in which the addition

of oxygen in the argon plasma for the sputtering of ITO does not negatively impact any layers underlying the ITO.

In the present invention, the oxidation that occurs during the ITO sputtering process is utilized to an advantage with respect to the layers underlying the ITO. More specifically, the metal oxidation resulting from the ITO sputter process is used to form a high work function metal-oxide layer **311** between the ITO **320** and the organic stack **200**. This structure results in an OLED with a top-emitting anode. In one embodiment of the invention, the thin MgAg film in the OLED discussed above is replaced with a layer of metal. This metal layer, preferably molybdenum (Mo), after it is oxidized during the ITO sputtering process, provides a conductive layer of molybdenum oxide (MoOx) with favorable properties of conductivity, transparency, and work function. It may also be possible to use this metal oxidation in a top-emitting cathode design.

OLEDs that use combinations of thin and thick top conductive layers **310** and **320**, whereby the thin layer provides desired injection properties and the thick layer provides low sheet resistance, are known. Furthermore, Mo is known as anode material in a top-emitting common cathode OLED design. Specifically, MoOx is a high work function conductive oxide and has been shown to perform as an injecting anode in OLEDs. See, for example: S. Tokito *et al.*, Journal of Physics D — Applied Physics, Vol. 29 (1996) pp. 2750-2753.

In the present invention, it is an innovation in OLED design to sputter the ITO thick upper layer **320** (for low sheet resistivity) and thereby to use the ITO sputtering process purposely to modify the underlying thin layer **311** of conductive material. The sputtering process transforms the thin injection layer from a metal to a conductive oxide useful as a thin injection layer. For example, the sputtering process converts Mo to MoOx.

In the conversion of thin injection layer **311** to a metal-oxide, it is a further innovation of the present invention to provide the added advantage of making the metal film, once transformed to an oxide, more transparent, thereby improving overall device efficiency in terms of brightness and/or required power. A further advantage is that the Mo of injection layer **311** may also stick better to the top organic in the organic stack **200** than other elements,

and in particular, it may stick much better than the Mg in the MgAg of known top-emitting cathode structures.

Objects of the Invention

It is therefore an object of the present invention to provide a more reliable organic light emitting diode (OLED) structure.

It is another object of the present invention to provide an improved OLED device fabricated using a conventional sputtering process.

It is still another object of the present invention to provide process for fabricating an improved OLED structure in which a relatively thick ITO layer is formed to provide a low resistance common electrode.

It is yet another object of the present invention to provide a process and an improved OLED device that permits use of additional oxygen in an argon plasma sputtering process yet still achieves desirable injection properties in the organic layers.

It is a further object of the present invention to provide an OLED device with the top-emitting low resistance electrode being DC or AC magnetron sputtered ITO, yet still achieve desirable injection properties into an immediately adjacent organic layer, via an intermediated oxidized metal/alloy layer.

It is still a further object of the present invention to provide a process and an OLED in which a thin metal layer, which is subsequently oxidized, protects underlying organic films during an ITO sputter deposition process.

It is yet a further object of the present invention to provide a process and an OLED with reduced risk of oxidation damage to organic layers underlying an ITO layer.

It is another object of the present invention to provide a process and an OLED wherein the oxidation of a metal layer transforms the metal from a relatively low work function material to a conductive high work function injector.

It is still another object of the present invention to provide a top-emitting OLED with improved transparency of the top layers.

It is yet another object of the present invention to provide a process and an OLED having improved device efficiency.

It is a further object of the present invention to provide an OLED with improved adhesion between the organic stack and the top electrode.

Additional objects and advantages of the invention are set forth, in part in the description which follows and, in part, will be apparent to one of ordinary skill in the art from the description and/or from the practice of the invention.

Brief Summary of the Invention

In response to the foregoing challenge, Applicant has developed an innovative, simple and economical organic light emitting diode (OLED) device. The OLED device comprises a bottom electrode, an organic stack for emitting light having a plurality of layers and disposed on the bottom electrode, a thin film layer disposed on the organic stack, and a top electrode disposed on the thin film layer. The OLED device further comprises the improvement comprising forming the thin film layer from a metal compound comprising at least one metal, and forming the top electrode such that the thin film layer ranges in thickness from about 10 Å up to about 100 nm and thereby allows precise control of hole injection.

The OLED device may be a top-emitting type, wherein the organic stack further comprises at least one layer of sublimed molecular film or at least one layer of a solution-processed polymer. The bottom electrode of the OLED device may further comprise a silicon substrate having driver electronics and patterned pixels formed on the substrate.

The top electrode of the disclosed OLED device may be formed by sputtering indium tin oxide (ITO) in an oxygenated plasma, whereby the metal compound of the thin film layer is oxidized by an oxidation process. The oxidation process may transform the metal compound from a relatively low work function metal compound to a high work function conductive metal oxide. For example, the low work function value may be about 4.2 eV and the high work function value may be greater than or equal to 4.5 eV. Further, the top electrode may be a relatively thick layer of ITO having high transparency and conductivity, and low sheet resistivity. In addition, the oxidized thin film layer may have improved

transparency and may protect the organic stack from oxidation damage by the ITO sputtering. In the OLED device disclosed, the oxygenated plasma may be an argon plasma.

In an alternate embodiment of the OLED device, the metal compound of the thin film layer may be oxidized by oxygen gas bleeding, rather than by an oxygenated argon plasma.

In the disclosed OLED device, the metal compound may be selected from the group comprising molybdenum, vanadium, ruthenium, nickel, and tantalum.

In one embodiment of the OLED device, the top electrode may be an anode.

In an alternate embodiment of the OLED device, the top electrode may be a cathode. In this alternate embodiment, the top cathode electrode is formed from ITO in an oxygenated argon plasma, whereby the metal compound of the thin film layer is transformed into a low work function conductive oxide.

In another alternate embodiment, the metal compound may be MgAg. In this alternate embodiment, the top electrode may be formed by sputtering from between 1 and 30 nm of ITO in an argon plasma. Further, the argon plasma may not contain additional oxygen. In this embodiment, the metal compound of the thin film layer may remain metallic and may not be oxidized by the sputtering of the ITO from the argon plasma.

Applicant further discloses a method of forming a top emitting organic light emitting diode (OLED) device comprising the steps of forming a bottom electrode; forming an organic stack on the bottom electrode; forming a thin film layer from a metal compound comprising at least one metal on the organic stack; and sputtering a top electrode from ITO in a plasma on the thin film layer, whereby the top electrode is a relatively thick layer of ITO and the thin film layer ranges in thickness from about 10 Å up to about 100 nm and thereby allows precise control of hole injection.

In the method of forming the disclosed OLED device, the thin film layer may be formed by evaporation or by sputtering. The organic stack may further comprise at least one layer of sublimed molecular film or at least one layer of a solution-processed polymer. The bottom electrode may further comprise a silicon substrate having driver electronics and patterned pixels formed on the substrate and the plasma may be an oxygenated argon plasma.

The method of forming the disclosed OLED device may further comprise the step of oxidizing the metal compound of the thin film layer. The oxidation step may transform the metal compound from a relatively low work function metal compound to a high work function conductive metal oxide. For example, the low work function value may be about 4.2 eV and the high work function value may be greater than or equal to 4.5 eV.

In the method of forming the disclosed OLED device, the top electrode may be a relatively thick layer of ITO having high transparency and conductivity, and low sheet resistivity. Further, the oxidized thin film layer may have improved transparency.

The method of forming the disclosed OLED device may further comprise the step of protecting the organic stack from oxidation damage from the ITO sputtering by the oxidized thin film layer. Further, the metal compound may be selected from the group comprising molybdenum, vanadium, ruthenium, nickel, and tantalum.

In an embodiment of the method of forming the disclosed OLED device, the top electrode may be an anode.

In an alternate embodiment of the method of forming the disclosed OLED device, the top electrode may be a cathode.

The method of forming the disclosed OLED device may further comprise the step of transforming the metal compound of the thin film layer into a low work function conductive oxide.

In an alternate embodiment of the method of forming the disclosed OLED device, the metal compound may be MgAg. In this alternate embodiment, the sputtering step may further comprise depositing from between 1 and 30 nm of ITO from an argon plasma to form the top electrode. In addition, the argon plasma may not contain additional oxygen, and the metal compound of the thin film layer may remain metallic and not be oxidized by the sputtering of the ITO from the argon plasma.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only, and are not restrictive of the invention as claimed. The accompanying drawings, which are incorporated herein by reference, and constitute part of the specification, illustrate certain embodiments of the

invention, and together with the detailed description, serve to explain the principles of the present invention.

Brief Description of the Drawings

The invention will now be described in conjunction with the following drawings in which like reference numerals designate like elements and wherein:

Fig. 1 is a cross-section in elevation of an OLED layer structure of the prior art; and

Fig. 2 is a cross-section in elevation of a preferred embodiment of the OLED layer structure of the present invention.

Detailed Description of the Preferred Embodiments of the Invention

With reference to Fig. 2, in a preferred embodiment of the invention, an organic light emitting diode (OLED) device **20** is provided. OLED **20** comprises bottom electrode **100** which preferably may be a silicon substrate with driver electronics and patterned pixels formed therein. One or more organic layers may be provided over the bottom electrode **100** in an organic stack **200**. A thin layer of an oxidized metal may provide the lower portion or injector portion **311** of top electrode **300** overlying organic stack **200**. Injector portion **311** may comprise, for example, molybdenum oxide (MoOx). An upper portion **320** of top electrode **300**, overlying injector portion **311**, may be provided by a layer of indium tin oxide (ITO). In this preferred embodiment, bottom electrode **100** serves as a cathode and top electrode **300** serves as an anode.

OLED **20** may be made by patterning a silicon chip substrate, using methods known in the art, to form integrated driver and pixel circuitry within the substrate, thereby forming bottom electrode **100**. An organic stack **200** may be provided on bottom electrode **100** also using known methods. Organic stack **200** may comprise one or more layers of sublimed molecular films or solution-processed materials, such as polymers.

Next, a thin layer of metal **311** may be provided, preferably but not necessarily by evaporation, overlying organic stack **200**. Metal layer **311** may be in the range of 5 to 200

Å thick, and should be selected from those metals that are conductive and have a relatively high work function when oxidized. For example, in the preferred embodiment, metal layer **311** is selected to be molybdenum (Mo), which when oxidized becomes MoOx. Mo metal layer **311** has a relatively low work function (approximately 4.2 eV) before being oxidized, but is converted to a conductive high work-function injector as a result of oxidation.

A further criterion for selecting the material for metal layer **311** is the relative transparency of the metal-oxide for the range of thicknesses for metal layer **311** in the particular emission spectra of organic stack **200**. With respect to this criterion, Mo is also believed to be a preferred material because it provides a desirable blend of transparency and conductivity properties, and in fact, may become more transparent after conversion to MoOx.

Metal layer **311** may be converted to a metal-oxide during the sputtering of upper conductive layer **320**. Upper conductive layer **320** may be selected from materials with a desirable blend of low sheet resistivity and relatively good transparency. In a preferred embodiment of the invention, upper conductive layer **320** comprises a layer of ITO which is sputtered onto the lower metal layer **311** using a DC or AC magnetron process with an argon plasma, with added oxygen. The oxygen in the argon plasma converts metal layer **311** into a metal oxide layer (for example, MoOx) during the sputtering process. The resulting metal-oxide layer, whose thickness may range from about 10 Å up to about 100 nm, provides desirable injection properties. Specifically, the metal-oxide layer permits more precise control of injection of holes, and facilitates balancing electron injection from the cathode with hole injection from the anode. The basic OLED **20** structure is complete upon the addition of ITO layer **320**.

The problem of unwanted oxidation of underlying layers during the sputtering of the ITO layer in the OLED is diminished in the present invention because MoOx is conductive and has a relatively high work function, making it a suitable injector material. Furthermore, MoOx has the favorable properties of providing a limited level of shielding of the underlying organic stack **200** from unwanted oxidation, and of becoming more transparent as a result of oxidation. It is evident that diminishing the problem experienced with the prior art process is dependent upon thin metal layer **311** being sufficiently oxidized during the sputtering

process. If the thin metal layer **311** is not sufficiently oxidized, particularly in the region where thin metal layer **311** contacts organic stack **200**, then unoxidized metal (for example, metallic Mo), which has a relatively low (and unsuitable) work function, may remain.

To assure adequate oxidation of thin metal layer **311**, it may be possible to tune the initial sputter process to optimize the oxidation of the Mo, particularly that portion which is adjacent to organic stack **200**. For example, a different plasma may be used to oxidize the Mo before the ITO deposition. Alternatively, the thin Mo layer may be oxidized with some oxygen gas bleeding, without plasma treatment.

In further alternate embodiments of the present invention, metal layer **311** may comprise metals other than Mo which, in their oxidized form, are high work function, transparent conductors. Such other metals include vanadium (V), ruthenium (Ru), nickel (Ni), tantalum (Ta), etc.— generally metal-oxides with work functions greater than or equal to 4.5 eV, but preferably greater than about 5 eV (see above-cited paper by Tokito *et al.*, which is hereby incorporated by reference).

In another alternate embodiment of the present invention, if it is desired that the immediate top electrode injector layer (a thin evaporated MgAg layer in the preferred top-emitting cathode OLED design) remain metallic, then it may be possible to sputter the first few nm (or tens of nm) of the ITO without additional oxygen in the ITO plasma. This would prevent oxidation of the underlying layers.

In yet another alternate embodiment of the present invention, the OLED is provided with a top-emitting cathode structure, that is, top electrode **300** is a cathode. In order to make top electrode **300** a cathode, the present invention contemplates evaporating a thin metal layer **311** and using the ITO plasma oxygen to make a low work function conductive oxide. Sub-stoichiometric oxides are believed to be at least slightly conductive and sub-stoichiometic alkaline-oxides can have very low effective work functions (for example, see the work by Professor Simon's group at the MPI in Stuttgart, Germany).

While this invention has been described in conjunction with specific embodiments thereof, it will be apparent to those skilled in the art that many alternatives, modifications and variations can be made to the disclosed OLED and method of fabrication without departing

from the scope and spirit of the invention. For example, in the above description, the thin layer of Mo metal to be oxidized by the ITO sputtering is evaporated onto the underlying organic stack. It is appreciated, however, that in alternative embodiments this thin layer of metal may alternatively be sputtered onto the organic stack. Accordingly, the preferred embodiments of the invention as set forth herein are intended to be illustrative, not limiting.

What Is Claimed Is:

1. In an organic light emitting diode (OLED) device having a bottom electrode; an organic stack for emitting light having a plurality of layers and disposed on said bottom electrode; a thin film layer disposed on said organic stack; and a top electrode disposed on said thin film layer; the improvement comprising:

forming said thin film layer from a metal compound comprising at least one metal; and

forming said top electrode such that said thin film layer ranges in thickness from about 10 Å up to about 100 nm and thereby allows precise control of hole injection.

2. The device of claim 1, wherein said device is a top-emitting type.

3. The device of claim 1, wherein said organic stack further comprises at least one layer of sublimed molecular film.

4. The device of claim 1, wherein said organic stack further comprises at least one layer of a solution-processed polymer.

5. The device of claim 1, wherein said bottom electrode further comprises a silicon substrate having driver electronics and patterned pixels formed on said substrate.

6. The device of claim 5, wherein said top electrode is formed by sputtering indium tin oxide (ITO) in an oxygenated plasma, whereby said metal compound of said thin film layer is oxidized by an oxidation process.

7. The device of claim 6, wherein said oxidation process transforms said metal compound from a relatively low work function metal compound to a high work function conductive metal oxide.

8. The device of claim 7, wherein said low work function value is about 4.2 eV and said high work function value is greater than or equal to 4.5 eV.

9. The device of claim 8, wherein said top electrode is a relatively thick layer of ITO having high transparency and conductivity, and low sheet resistivity.

10. The device of claim 9, wherein said oxidized thin film layer has improved transparency.

11. The device of claim 10, wherein said oxidized thin film layer protects said organic stack from oxidation damage by said ITO sputtering.

12. The device of claim 11, wherein said oxygenated plasma is an argon plasma.

13. The device of claim 1, wherein said metal compound of said thin film layer is oxidized by oxygen gas bleeding.

14. The device of claim 1, wherein said metal compound is selected from the group comprising molybdenum, vanadium, ruthenium, nickel, and tantalum.

15. The device of claim 1, wherein said top electrode is an anode.

16. The device of claim 1, wherein said top electrode is a cathode.

17. The device of claim 16, wherein said top cathode electrode is formed from ITO in an oxygenated argon plasma, whereby said metal compound of said thin film layer is transformed into a low work function conductive oxide.

18. The device of claim 1, wherein said metal compound is MgAg.

19. The device of claim 18, wherein said top electrode is formed by sputtering between 1 and 30 nm of ITO in an argon plasma.

20. The device of claim 19, wherein said argon plasma does not contain additional oxygen.

21. The device of claim 20, wherein said metal compound of said thin film layer remains metallic and is not oxidized by the sputtering of said ITO from said argon plasma.

22. In a top-emitting organic light emitting diode (OLED) device having a bottom electrode; an organic stack for emitting light having a plurality of layers and disposed on said bottom electrode; a thin film layer disposed on said organic stack; and a top electrode disposed on said thin film layer; the improvement comprising:

forming said thin film layer from a metal compound comprising at least one metal; and

forming said top electrode by sputtering indium tin oxide (ITO) in an oxygenated argon plasma, whereby said metal compound of said thin film layer is oxidized by an oxidation process to range in thickness from about 10 Å up to about 100 nm and thereby allows precise control of hole injection.

23. The device of claim 22, wherein said oxidation process transforms said metal compound from a relatively low work function metal compound to a high work function conductive metal oxide.

24. The device of claim 23, wherein said low work function value is about 4.2 eV and said high work function value is greater than or equal to 4.5 eV.

25. The device of claim 24, wherein said metal compound is selected from the group comprising molybdenum, vanadium, ruthenium, nickel, and tantalum.

26. The device of claim 24, wherein said top electrode is an anode.

27. The device of claim 22, wherein said top electrode is a cathode.

28. The device of claim 27, wherein said metal compound of said thin film layer is transformed into a low work function conductive oxide.

29. A method of forming a top emitting organic light emitting diode (OLED) device comprising the steps of:

forming a bottom electrode;

forming an organic stack on said bottom electrode;

forming a thin film layer from a metal compound comprising at least one metal on said organic stack;

sputtering a top electrode from ITO in a plasma on said thin film layer, whereby said top electrode is a relatively thick layer of ITO and said thin film layer ranges in thickness from about 10 Å up to about 100 nm and thereby allows precise control of hole injection.

30. The method of claim 29, wherein said thin film layer is formed by evaporation.

31. The method of claim 29, wherein said thin film layer is formed by sputtering.

32. The method of claim 29, wherein said organic stack further comprises at least one layer of sublimed molecular film.

33. The method of claim 29, wherein said organic stack further comprises at least one layer of a solution-processed polymer.

34. The method of claim 29, wherein said bottom electrode further comprises a silicon substrate having driver electronics and patterned pixels formed on said substrate.

35. The method of claim 34, wherein said plasma is oxygenated.

36. The method of claim 35, wherein said oxygenated plasma is an argon plasma.

37. The method of claim 36, further comprising the step of oxidizing said metal compound of said thin film layer.

38. The method of claim 37, wherein said oxidation step transforms said metal compound from a relatively low work function metal compound to a high work function conductive metal oxide.

39. The method of claim 38, wherein said low work function value is about 4.2 eV and said high work function value is greater than or equal to 4.5 eV.

40. The method of claim 39, wherein said top electrode is a relatively thick layer of ITO having high transparency and conductivity, and low sheet resistivity.

41. The method of claim 40, wherein said oxidized thin film layer has improved transparency.

42. The method of claim 41, further comprising the step of protecting said organic stack from oxidation damage from said ITO sputtering by said oxidized thin film layer.

43. The method of claim 42, wherein said metal compound is selected from the group comprising molybdenum, vanadium, ruthenium, nickel, and tantalum.

44. The method of claim 43, wherein said top electrode is an anode.

45. The method of claim 37, wherein said top electrode is a cathode.

46. The method of claim 45, further comprising the step of transforming said metal compound of said thin film layer into a low work function conductive oxide.

47. The method of claim 34, wherein said metal compound is MgAg.

48. The method of claim 47, wherein said sputtering step further comprises depositing from between 1 and 30 nm of ITO from an argon plasma to form said top electrode.

49. The method of claim 48, wherein said argon plasma does not contain additional oxygen.

50. The method of claim 49, wherein said metal compound of said thin film layer remains metallic and is not oxidized by the sputtering of said ITO from said argon plasma.

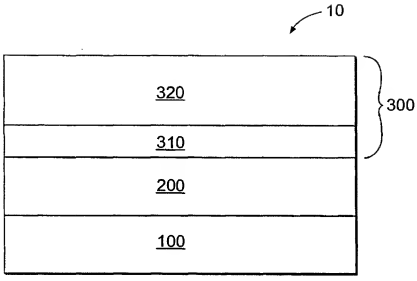

FIG. 1
(PRIOR ART)

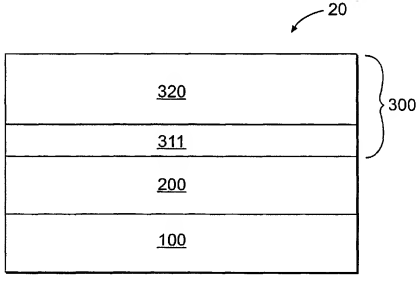

FIG. 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/22838

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) :H01L 35/24
US CL : 257/40
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 257/40, 44, 94

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,920,080 A [Jones] 06 July 1999 (06/07/99), the entire reference.	1-2, 5-24, 25-32, 34-50
X	US 5,714,838 A [Haight et al.] 03 February 1998 (03/02/98), the entire reference.	1-7, 9-11, 14-16, 18-19, 22-23, 26-29, 31-34, 37-38, 40-42, 44-48
X,P	US 5,981,306 A [Burrows et al.] 09 November 1999 (09/11/99), the entire reference.	1-3, 6-7, 9-11, 14-16, 18-19, 21-23, 26-29, 31, 34, 38, 40-42, 44-47

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
06 OCTOBER 2000	14 NOV 2000
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Authorized officer WAI-SING LOUIE
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